Energy Resilience:

Critical Load Support in Commercial and Residential Applications

Efficiency Vermont R&D Project: Resilience

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Contents

Executive Summary

Efficiency Vermont's portfolio of projects relating to energy resilience research consists of three independent investigations into materials and methods for increasing energy resilience in commercial and residential settings:

- **DC Microgrid Community:** A microgrid community of homes and other buildings using direct current as the primary electricity delivery source
- **Phase Change Materials:** The potential for increased use of phase change materials for a variety of applications
- **Residential Energy Resilience:** Assessing thermal resilience using space temperature float time to mitigate the impacts of power outages

These projects began in 2021 and continued throughout 2022. The studies examine technologies and approaches and their effects on energy resilience, with considerations of coincident improvements in system energy efficiency.

DC MICROGRID COMMUNITY

An affordable housing complex in Randolph, Vermont, Salisbury Square, is a prototype community demonstrating the feasibility and energy impacts of a direct-current (DC) electrical system in a microgrid. Upon the project's completion in 2023, system designers expect it to provide uninterrupted energy to critical loads during a power outage, while offering grid support services during normal operation. The project will also deliver more solar energy for end uses than a comparable alternating-current (AC) system, because it will have fewer inverters in the system.

In 2021, the system design team substantially completed the initial phase for a community-based DC electrical distribution and microgrid system in the income-qualified development. In 2022, the design team solicited and reviewed general contractor bids for the new homes and evaluated the feasibility of a Ford F150 Lightning truck, an electric vehicle, situated at the site. The design team also explored microgrid component ownership structure options with Green Mountain Power, the community's local electric utility.

PHASE CHANGE MATERIALS

An evaluation of the effects of phase change material (PCM) on heating and air-conditioning system efficiency and temperature maintenance, begun in 2021, has continued into 2022. The Efficiency Vermont research team has hypothesized that PCM can improve heating system efficiency by releasing stored heat into a space, so that the system can lengthen cycle times, reduce total operating hours, and participate in flexible load management programs. The outcomes of this investigation have significant implications for building operations efficiency and reductions in greenhouse gas (GHG) emissions—and resilience during power outages, because PCMs are a heat storage medium for space conditioning.

The research team designed PCM installations at two sites in 2021 to demonstrate passive and active PCM integration. In terms of results to date, PCM tiles installed in a small office showed no change, compared to historical data, in energy use from its propane boiler. These outcomes are primarily a function of differences in tile temperature, relative to space temperature, and range of operability around the temperature set point of the tiles.

A PCM tank specified for the second building in this study is now installed at the site. After fixing an error in the PCM procurement, the system is expected to be operational and producing routine data on indoor space temperature by winter 2022. All necessary metering is in place to begin collecting the data and entering them into an OpenStudio® whole-building energy modeling software platform.

RESIDENTIAL ENERGY RESILIENCE

The Residential Energy Resilience study used OpenStudio and field data to create a model home. The research team investigated methods to manipulate the modeling software to produce data characterizing the relationship among indoor temperature, outdoor temperature, and building shell air leakage. The model will be used to correlate data between airtightness and temperature decay to demonstrate how those factors interact to affect space comfort during a power outage. The data can show homeowners how much space temperature "float time"—the amount of time it takes before the space becomes uncomfortable—they can expect at varying outage durations, indoor, and outdoor temperatures. The data also can show the amount of additional weatherization they need to increase the float time to an optimal duration.

The study revealed modeling challenges in OpenStudio that the modeling team addressed during the year with the National Renewable Energy Laboratory (NREL) to enhance the software's functionality and establish ways to effectively model temperature float time. These issues were unforeseen at the beginning of the study, so OpenStudio was unable to produce the dataset to show the space temperature float time relationship, but the improved modeling functionality will enable the dataset with further work in the tool.

As the study continues to move forward, the research team will further investigate homes built on slabs containing radiant heat to determine the effect on interior temperature resilience when occupants preheat the slab in anticipation of a power outage or demand response event. Preheating is achieved by raising the space temperature setpoint ahead of the expected event.

This report presents the details of these three studies and offers quantitative and qualitative conclusions about them. It also provides study updates that are useful for design and construction industry professionals and regulators interested in advancing resilience through energy efficiency projects.

Introduction

Energy resilience is a set of assets and a plan to meet the minimum energy needs to protect life and property during a power outage. Increasingly frequent extreme weather events and rising energy costs are driving a growing number of consumers to explore ways to take control over their ability to achieve secure and reliable energy infrastructure in their homes. The resulting resilience in these buildings can be described as energy assurance.

The electricity grid is evolving toward incorporating micro-power into its generation mix. Because of this, producers and consumers can now use storage and distribution site-specific energy resilience strategies to manage grid operations and reduce peak load demand.

In 2020, Efficiency Vermont created the formulas and variables necessary for determining the best return on investment in energy resilience assets.[1] This energy resilience portfolio of studies applies that research to three independent investigations into materials and methods of increasing energy resilience in commercial and residential settings. Each multi-year study began in 2021 and has continued through 2022 and offers Vermont-based experiences in designing and implementing energy resilience technologies that can benefit the design and construction industries nationwide.

The portfolio of energy resilience investigations evaluates technologies and infrastructure that offer both simple, inexpensive options and large capital projects. Each of the studies is unrelated to the others; however, once Efficiency Vermont researchers fully understand the energy impacts of each study, the research team will have sufficient information to explore their possible integration.

Microgrids, phase change materials, and home batteries are beginning to enter the market and attract attention for their energy savings, energy assurance, and financial benefits. As new technologies, they offer only limited data for owners. Thus, it is still a challenge for owners to determine whether the investment will lead to long-term, cash-positive benefits. These studies are designed to provide new data that support owners in determining whether these systems will support their energy and construction objectives and give them confidence in the investments they make.

The three projects are:

- DC Microgrid Community: A microgrid community of homes and other buildings using direct current as the primary electricity delivery source
- Phase Change Materials: The potential for increased use of phase change materials for a variety of applications

[1] Ross, Allison, "Energy Resilience Return on Investment," Efficiency Vermont R&D Program Report, 2020.

- **Residential Energy Resilience:** The effectiveness of using data to determine optimal weatherization needs, and of deploying space-heating strategies for increasing the resilience of homes, to mitigate the impacts of power outages

Direct Current Microgrid

Randolph Area Community Development Corporation (RACDC)'s Salisbury Square in Randolph, Vermont, is now ready to break ground on the construction of a planned, unique, direct-current (DC) microgrid serving a low- and moderate-income community.

Peter Schneider, a Senior Engineering Consultant with Efficiency Vermont, is the project's technical and engineering partner. As of the date of this report, RACDC is closing the financial arrangements with the funders, and will subsequently break ground on construction of the homes. Throughout 2022, the project partners had discussions with potential general contractors ahead of soliciting bids to construct the zero-energy modular (ZEM) community on the brownfield site. The net-zero-energy homes are one of the key features that will enable a direct current (DC) microgrid in the community that can support critical loads during an adverse event. During normal power operation, the project can also provide grid benefits to the utility, and economic benefits to the community.

The microgrid will consist of 157-kilowatts (kW) of solar power, distributed across building roofs and serving as a carport, producing an estimated 150-megawatt hours (MWh) per year, as shown in Figure 1. The generation will be complemented with 980-kilowatt hours (kWh) of battery storage, centrally located in the community's existing bookkeeping building's basement. The existing bookkeeping building will be converted into a community house which will serve as an emergency shelter when necessary.

Figure 1: Photo voltaic generation estimates from NREL's PVWatts. Model courtesy of Direct Energy Partners.

VEIC Salisbury Square Housing - Generation - Annual Energy Estimates

Lot #	Type	Architecture Plans Name	Building Orientation	Tilt [deg]	Area for Solar [ft x ft]	Solar [kW]	PVWatts Estimate (DC Output) [kWh]	Peak May-Sep [kW]	Peak Oct-Apr [kW]
L#1	3BD/2FL	Traditional 3 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
L#2a	4PLEX/2FL	4PLEX/2FL Building a	N-S	10	14 x 40	15.0	14,782	12	11.7
L#2b	4PLEX/2FL	4PLEX/2FL Building b	E-W	10	14 x 40	15.0	14,487	11.8	11.5
L#3	3BD/2FL	Traditional 3 Bedroom	E-W	30	30 x 19	5.0	5,633	4.4	4.6
L#4	3BD/2FL	Traditional 3 Bedroom	E-W	30	30 x 19	5.0	5,633	4.4	4.6
L#5	3BD/2FL (alt)	Contemporary 3 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
L#6	3BD/2FL	Traditional 3 Bedroom	N-S	2	14 x 40	7.5	7,391	5.9	5.7
L#7	3BD/2FL	Traditional 3 Bedroom	E-W	30	30 x 19	5.0	5,633	4.4	4.6
L#8	3BD/2FL	Traditional 3 Bedroom	E-W	30	30 x 19	5.0	5,633	4.4	4.6
L#9	2BD/2FL	Traditional 2 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
L#10	3BD/2FL	Traditional 3 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
L#11	2BD/2FL	Traditional 2 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
L#12	3BD/2FL (alt)	Contemporary 3 Bedroom	E-W	2	14 x 40	7.5	7,243	5.9	5.7
?	CARPORT-6	6-Car Solar Canopy	E-W	30	23 x 82	23.0	29,218	17.5	19.2
?	CARPORT-4	4-Car Solar Canopy	E-W	30	23 x 56	15.0	19,055	11.4	12.5
Total						140.5	**150,923**		

Notes:

DC VERSUS AC EFFICIENCY PERFORMANCE

The long-term objectives of this project involve a comprehensive evaluation of the energy efficiency improvement of a DC electrical system over an alternating-current (AC) system within a community microgrid because the renewable generation in DC form should experience fewer losses in distribution when there are fewer inverters in the system. According to the feasibility study conducted by Dusan Brhlik of Direct Energy Partners and Craig Burton of Interface Engineering for this project, the DC microgrid should show a 5 percent energy efficiency improvement over an AC system and adopting DC-capable equipment should save an additional 5 percent.

Building level modeling simulations at Lawrence Berkeley National Laboratory showed an average 11 percent efficiency increase using DC over AC.[2] The savings increased when the modeled system was paired with renewable energy production and battery storage; further, the system could attain 17.5 percent energy savings when the system was designed with solar, battery, and converter capacities higher than baseline for the theoretical building.

DECISION POINTS

Completed Decisions. Project partners made critical decisions to progress planning for the direct-current electrical system. Homes will have a DC and an AC electrical system to accommodate legacy AC devices (Figure 2). The project objective is to specify major equipment with DC capability. Discussions with manufacturers have resulted in confirmed specifications for appliances, lighting, and some plug receptacles. The manufacturer LG has agreed to provide DC kitchen appliances and laundry equipment (Figure 3 and Image 1). Although the technology is ready, the manufacturer will need to have the models UL tested. Due to time constraints, the models will not be UL listed at time of installation, and the design team will need to ensure the testing data are sufficient to meet fire code.

[2] Gerber, Daniel L., et al. "A Simulation Based Comparison of DC Versus AC Power Distribution Networks in Buildings", Lawrence Berkley National Laboratory, June 2017.

Figure 2. Proposed electrical service in a one-bedroom home. Drawing courtesy of David Pill, Pill-Maharam Architects.

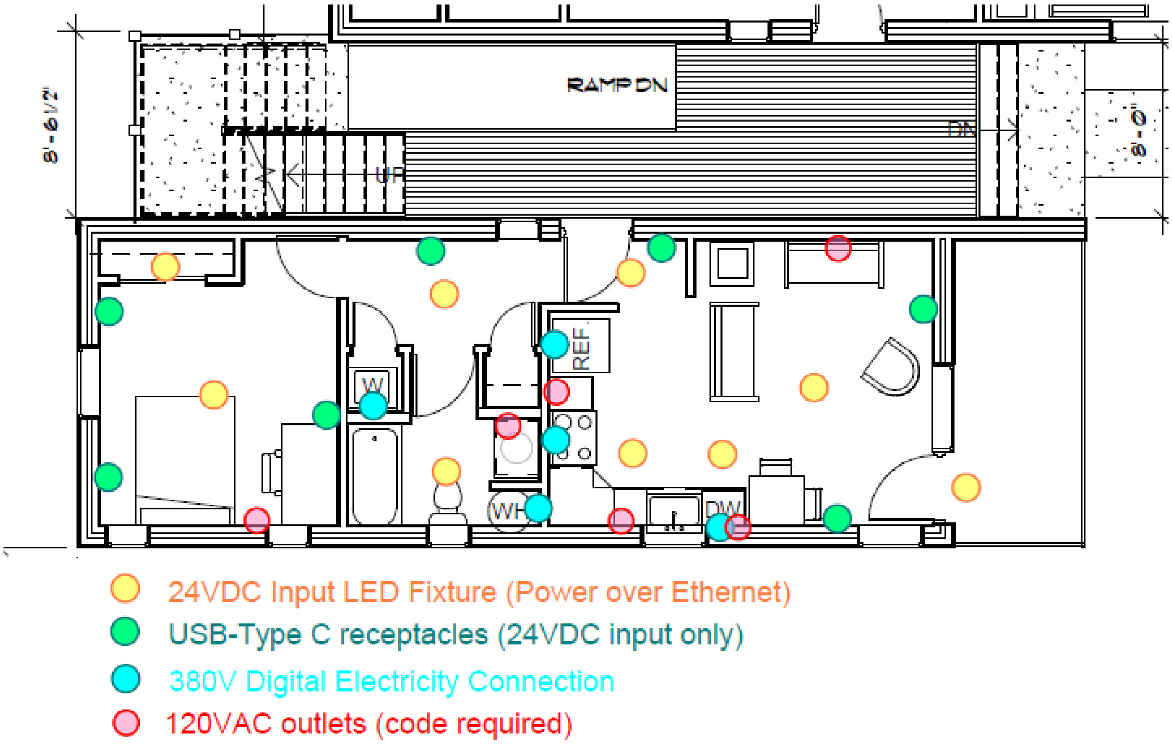
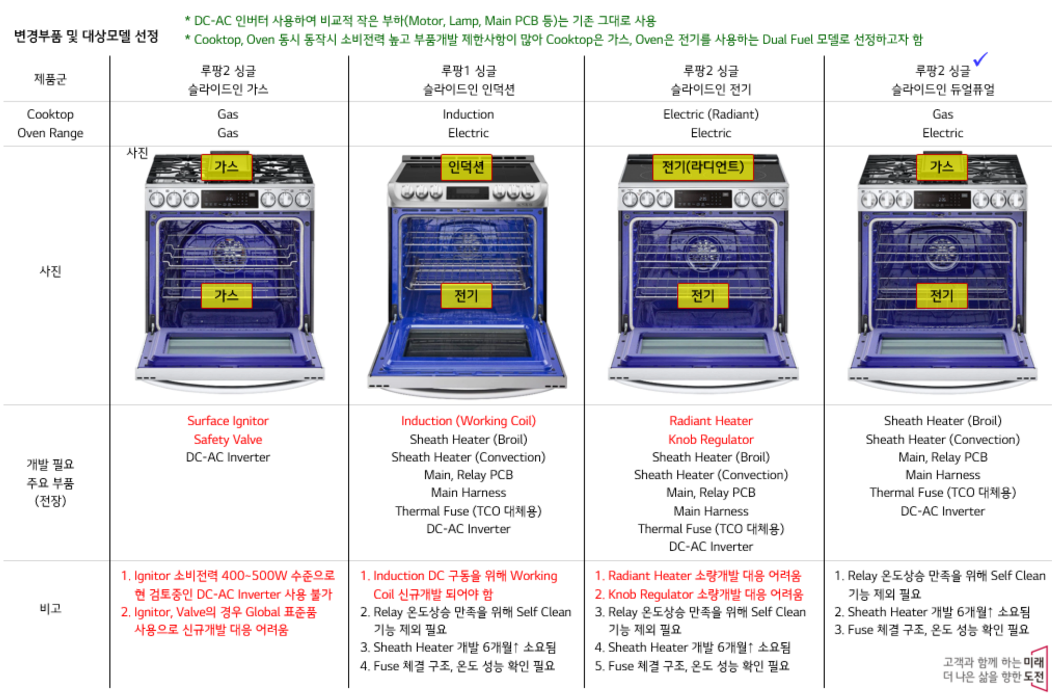


Figure 3. DC range models and the fuel options. Drawing courtesy of LG.



변경부품 및 대상모델 선정

* DC-AC 인버터 사용하여 비교적 작은 부하(Motor, Lamp, Main PCB 등)는 기존 그대로 사용
* Cooktop, Oven 동시 동작시 소비전력 높고 부품개발 제한사항이 많아 Cooktop은 가스, Oven은 전기를 사용하는 Dual Fuel 모델로 선정하고자 함

제품군	루팡2 싱글 슬라이드인 가스	루팡1 싱글 슬라이드인 인덕션	루팡2 싱글 슬라이드인 전기	루팡2 싱글 ✓ 슬라이드인 듀얼퓨얼
Cooktop Oven Range	Gas Gas	Induction Electric	Electric (Radiant) Electric	Gas Electric
사진	가스 가스	인덕션 전기	전기(라디언트) 전기	가스 전기
개발 필요 주요 부품 (전장)	Surface Ignitor Safety Valve DC-AC Inverter	Induction (Working Coil) Sheath Heater (Broil) Sheath Heater (Convection) Main, Relay PCB Main Harness Thermal Fuse (TCO 대체용) DC-AC Inverter	Radiant Heater Knob Regulator Sheath Heater (Broil) Sheath Heater (Convection) Main, Relay PCB Main Harness Thermal Fuse (TCO 대체용) DC-AC Inverter	Sheath Heater (Broil) Sheath Heater (Convection) Main, Relay PCB Main Harness Thermal Fuse (TCO 대체용) DC-AC Inverter
비고	1. Ignitor 소비전력 400~500W 수준으로 현 검토중인 DC-AC Inverter 사용 불가 2. Ignitor, Valve의 경우 Global 표준품 사용으로 신규개발 대응 어려움	1. Induction DC 구동을 위해 Working Coil 신규개발 되어야 함 2. Relay 온도상승 만족을 위해 Self Clean 기능 제외 필요 3. Sheath Heater 개발 6개월↑ 소요됨 4. Fuse 체결 구조, 온도 성능 확인 필요	1. Radiant Heater 소량개발 대응 어려움 2. Knob Regulator 소량개발 대응 어려움 3. Relay 온도상승 만족을 위해 Self Clean 기능 제외 필요 4. Sheath Heater 개발 6개월↑ 소요됨 5. Fuse 체결 구조, 온도 성능 확인 필요	1. Relay 온도상승 만족을 위해 Self Clean 기능 제외 필요 2. Sheath Heater 개발 6개월↑ 소요됨 3. Fuse 체결 구조, 온도 성능 확인 필요

고객과 함께 하는 미래
더 나은 삶을 향한 도전

Image 1: DC appliances. Photo courtesy of Peter Schneider.

Ongoing Decisions. Efficiency Vermont and the design team are continuing discussions with manufacturers regarding specifications on DC-capable heat pumps, heat pump water heaters, and ventilation. LG and Blue Planet Energy are also discussing siting requirements for the lithium-ion batteries, because they will be installed in Salisbury Square's bookkeeping building's basement.

Manufacturer discussions have indicated that LG is the furthest along in DC-capable equipment, but they do not have robust product lines for heat pump water heaters or cold-climate heat pumps. They have recently introduced a standard AC heat pump water heater, and the research team determined that because it is so new to the market, LG may not have the resource capacity to produce a DC version in time for construction. LG's small line of cold-climate heat pumps also means they have few options for producing a unit with DC capability. The design team's evaluation is ongoing, and the decision to adopt DC HVAC equipment is to be determined.

The project team is also evaluating the feasibility of staging a Ford F150 Lightening at the development. The truck could serve as additional battery power to the microgrid and provide a utility vehicle under a rental program accessible to the community. There are a number of questions yet to inform a final decision. A vehicle owner and rental program operating procedure would be required, the vehicle would need to be designed into the microgrid to account for its energy storage, and the owner would need to overcome the currently very long lead time for the vehicle.

ENERGY MODELS

The modeling team modeled energy loads using National Renewable Energy Laboratory's (NREL) HPXML software and REM/Rate™ software to inform equipment sizing for the microgrid. There were significant differences between the outputs for these two models. The differences are likely due to assumptions built into the software packages. Figure 4 shows the estimated energy use from NREL's UrbanOpt tool. REM/Rate's estimates were higher for each home than UrbanOpt. Studies the design team referenced during modeling indicated that actual use can vary by roughly 25% from the model. There are plans to monitor energy use in the homes after occupancy to determine how closely the models estimated energy usage.

Figure 1: Load estimates from UrbanOpt modeling. Model courtesy of Direct Energy Partners.

VEIC Salisbury Square Housing - Load - Annual Energy Estimates

Lot #	Type	Architecture Plans Name	Peak May-Sep [kW]	Peak Oct-Apr [kW]	Annual Energy [kWh/yr]	Cooling [kWh/yr]	Heating [kWh/yr]	Water Heating (Electrical) [kWh/yr]	Lights [kWh/yr]	Appliances [kWh/yr]	Ventilation [kWh/yr]	Miscellaneous [kWh/yr]	Electric vehicle charging [kWh/yr]
L#1	3BD/2FL	Traditional 3 Bedroom	6	16	10,459	126	4,987	895	610	1,701	362	1,778	0
L#2a	4PLEX/2FL	4PLEX/2FL Building a	3	6	6,777	84	1,266	1,244	1,045	1,470	225	1,443	0
L#2a	4PLEX/2FL	4PLEX/2FL Building a	3	6	6,819	124	1,277	1,235	1,045	1,470	225	1,443	0
L#2a	4PLEX/2FL	4PLEX/2FL Building a	3	6	6,587	164	1,009	1,231	1,045	1,470	225	1,443	0
L#2a	4PLEX/2FL	4PLEX/2FL Building a	3	6	6,570	158	1,035	1,194	1,045	1,470	225	1,443	0
L#2b	4PLEX/2FL	4PLEX/2FL Building b	3	6	6,777	84	1,266	1,244	1,045	1,470	225	1,443	0
L#2b	4PLEX/2FL	4PLEX/2FL Building b	3	6	6,819	124	1,277	1,235	1,045	1,470	225	1,443	0
L#2b	4PLEX/2FL	4PLEX/2FL Building b	3	6	6,587	164	1,009	1,231	1,045	1,470	225	1,443	0
L#2b	4PLEX/2FL	4PLEX/2FL Building b	3	6	6,570	158	1,035	1,194	1,045	1,470	225	1,443	0
L#3	3BD/2FL	Traditional 3 Bedroom	6	16	14,705	77	7,547	1,898	731	1,932	472	2,048	0
L#4	3BD/2FL	Traditional 3 Bedroom	6	16	14,705	77	7,547	1,898	731	1,932	472	2,048	0
L#5	3BD/2FL (alt)	Contemporary 3 Bedroom	6	14	12,863	117	5,655	1,895	737	1,932	475	2,052	0
L#6	3BD/2FL	Traditional 3 Bedroom	6	16	10,495	111	4,387	1,546	610	1,701	362	1,778	0
L#7	3BD/2FL	Traditional 3 Bedroom	6	16	14,705	77	7,547	1,898	731	1,932	472	2,048	0
L#8	3BD/2FL	Traditional 3 Bedroom	6	16	14,705	77	7,547	1,898	731	1,932	472	2,048	0
L#9	2BD/2FL	Traditional 2 Bedroom	7	9	12,863	117	5,655	1,895	737	1,932	475	2,052	0
L#10	3BD/2FL	Traditional 3 Bedroom	6	16	10,459	126	4,987	895	610	1,701	362	1,778	0
L#11	2BD/2FL	Traditional 2 Bedroom	7	9	12,863	117	5,655	1,895	737	1,932	475	2,052	0
L#12	3BD/2FL (alt)	Contemporary 3 Bedroom	6	14	10,459	126	4,987	895	610	1,701	362	1,778	0
?	CARPORT-6	6-Car Solar Canopy	66	66	44,045	0	0	0	365	0	0	0	43,680
?	CARPORT-4	4-Car Solar Canopy	44	44	29,339	0	0	0	219	0	0	0	29,120
Total					266,171	2,208	75,675	27,316	16,519	32,088	6,561	33,004	72,800

Notes:
(1) L#2b 4PLEX/2FL N/S estimate basted on load profile L#2a 4PLEX/2FL E/W

DISTRIBUTION UTILITY INTEGRATION

The design team continues to engage with Green Mountain Power, the utility serving the site, to plan the ownership structure for the microgrid equipment. The ownership model is unique for the community. RACDC prefers that Green Mountain Power own and operate the microgrid and its components; this reduces the need for RACDC to acquire the skills necessary to operate the microgrid. Green Mountain Power must investigate regulatory details that can answer questions about legal rights to access the system. The permitting process for the microgrid may take 8 to 12 months and includes evaluating the system's effects on regional grid operations. The Vermont Department of Public Service must approve the project before it will be allowed to go forward. A project delay is costly for RACDC because it must adhere to requirements from grantors of the funds it receives for the work that it does for low-income residents. Therefore, navigating the approval process tightly will be critical.

NEXT STEPS

The information presented here has also been described in greater detail in the *Proceedings of the 2022 ACEEE (American Council for an Energy-Efficient Economy) Summer Study of Energy*

Efficiency in Buildings. That paper foresees the pathway to scalability, and lays out proposed research steps relating to:

- More advanced modeling of passive survivability building resilience during power outages
- Distinct modeling in building energy management of alternating current vs. DC building loads, and their connection to the grid and microgrids
- Modeling of electric vehicles in backup power for buildings
- Time-dependent photovoltaic power de-rating, to show the impact on the power generation profile shape for snowy conditions. This data will refine modeled estimates of renewable energy production throughout the year.

Project construction is expected to begin by the end of 2022 and take approximately 2 years. Efficiency Vermont will monitor the construction progress throughout the project, capturing data for comprehensive best practices. When the project is completed and operating online, system performance data will be integral to assessing real-world performance and comparing it to estimated performance and to modeled performance of a comparable AC microgrid.

Phase Change Materials

Phase change materials (PCM) in the form of tiles or blankets have been tested in various applications. San Diego Gas and Electric studied a biobased PCM tile in a new construction project. Because the building was new construction, there was no baseline energy usage data available, and EnergyPlus was used to estimate the baseline. The model showed energy savings, however, the authors were not confident in the results due to errors in the modeling software. They also had concerns about the complex VRF system and its accuracy in the model.[3]

The utility further studied PCM tiles in a high school under cooling conditions to assess whether the rooftop units achieved at least 30% energy savings. The results showed higher overall energy consumption in the classrooms with PCM installed but reduced compressor energy use, however, the reduction was within the standard deviation, so the authors concluded that the PCM had no effect on energy consumption.[4] The study was conducted using only four classrooms and excluded the rest of the building, so air flow to and from excluded areas of the building may have influenced the PCM performance.

A study for Southern California Edison compared preheating and precooling in the California market to determine whether the increase in energy to achieve preconditioning could provide an overall energy reduction later in the day. The study included testing with PCM installed in the building. It showed that the PCM increased the energy use during preconditioning and could further reduce energy use later in the day, but the PCM required enough of a temperature swing to cause it to melt or crystalize. The study's authors concluded that programming the temperature shifts into the thermostat without PCM resulted in significant energy savings and that adding PCM to the same temperature program did not result in enough additional energy savings to justify PCM cost, though there was a caveat that the PCM in the study was not commercially available, therefore there were no cost data.[5]

Efficiency Vermont added to the industry's body of PCM research by testing PCM tiles in an office building located in a cold climate.

PHASE CHANGE TILES

Mann and Machine, an auto repair and service center in Richmond, Vermont, has installed 600 square feet of Insolcorp salt hydrate-based PCM tiles within its first- and second-floor office spaces. Additional garage space is not included in the study. The office space has traditionally been heated with a propane boiler. Efficiency Vermont analyzed historic data from propane

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[3] Phase Change Material in New Construction Training Center. Emerging Technologies Program: San Diego Gas and Electric. November 2017. https://www.etcc-ca.com/reports/phase-change-material-new-construction-training-center.
[4] Rogers, Michael and James Bottomley. ET17SDG1021: Phase Change Material Drop-Ceiling Application in Schools: San Diego Gas and Electric. June 8, 2018. https://www.etcc-ca.com/reports/phase-change-material-drop-ceiling-application-schools?dl=1667938614.
[5] Wilcox, Bruce. Grange House 2018 Cooling Season and 2018-19 Heating Season Load Shifting with and without Phase Change Materials: Southern California Edison. December 31, 2019. https://www.etcc-ca.com/reports/central-valley-research-homes-grange-house-2018-cooling-season-and-2018-19-heating-season?dl=1667942776.

delivery records for two years prior to the tile installation and compared that information to data from the heating season of 2021 to 2022.

Study Methods

Propane delivery records for the Mann and Machine location were provided to establish propane use in the space before and after tile installation. Preinstallation delivery records ran from January 1, 2019, to October 29, 2021; post-installation delivery records ran from December 2021 to May 2022.

The indoor set temperature point during the study period was verified by the owner.

Following Insolcorp's installation instructions, the building owner's general contractor installed 600 square feet of 2-foot-by-2-foot salt hydrate PCM tiles above the flat drop ceiling on the first and second floors on December 6, 2021 (Figure 6). The tiles covered 60% of the total ceiling area on the first and second floors.

Image 2: Top left: PCM tiles installed above a drop ceiling tile on the first floor, Top right: PCM tiles installed above drop ceiling tiles on the second floor, Bottom: view of PCM tiles during installation process.

Analysis

In May 2022, at the end of the 2021-2022 heating season, the Efficiency Vermont research team normalized propane use data for weather and compared the pre- and post-installation propane consumption data to assess the impact of the PCM tiles on heating fuel consumption. The research team used heating degree day data for the Burlington International Airport site (weather station KBTV) from www.degreedays.net at daily intervals, and then binned the data by heating season. The research team also binned propane delivery data in the same heating season bins. The owner reported the heat setpoint for the test year at 72° F on the first floor and 72° F on the second floor. The research team then compared the respective data to a 65° F base temperature. The base temperature was chosen because it is a commonly used baseline in Efficiency Vermont projects.

The research team modeled the data in Python, using a regression analysis to determine whether there was a difference in propane use after the PCM tiles were installed. The regression model predicts what the propane use should be which is then compared to the actual use.

Results

Python created a formula to describe propane use based on the propane delivered before the PCM tiles were installed.

$$predictedFuelUsage = 2.584 + 0.088 * HDD_{in_{period}} - 0.207 * NumDaysInPeriod$$

Efficiency Vermont used the formula to model how much propane the space will use over time assuming conditions remain the same. The “period” is the number of days between each propane delivery. Propane deliveries are automated, and the vendor’s delivery schedule is not a regularly cyclical period. If the PCM tiles reduced the energy the space consumed, the actual gallons used in each propane delivery period should be lower than what the model predicts.

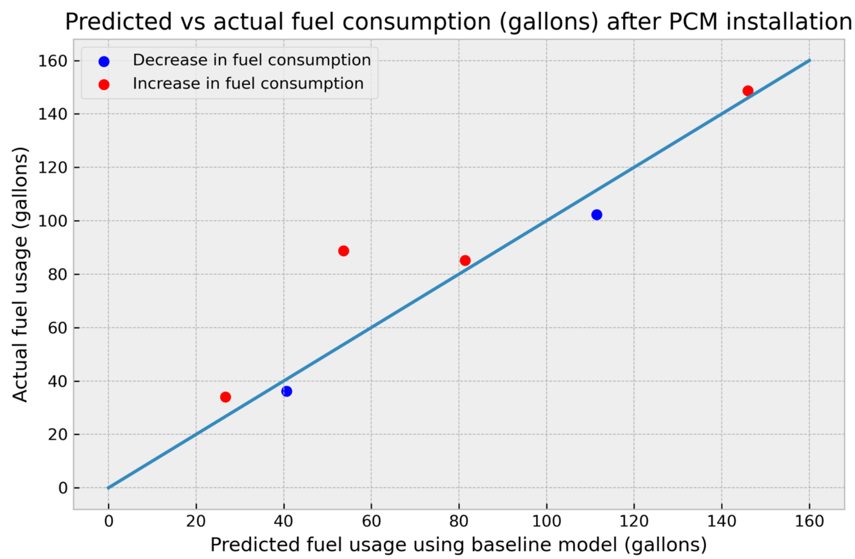
The data showed no increase in fuel use efficiency during the heating season. Figure 5 shows the propane data for each time period between deliveries. The first and last time periods show lower propane use than the baseline model predicts indicating that the PCM tiles helped to reduce energy use. The remaining time periods show more propane use than the baseline predicted.

Figure 2: Propane use within each time interval during the 2021-2022 heating season at Mann and Machine.

Actual fuel usage (gallons)	Predicted fuel usage using baseline model (gallons)	Savings: predicted - actual usage (gallons)	HDD65 in period	HDD65 per day	Drop date	Period start date	Period end date	Number of days in period	Predicted gallons per day	Actual gallons per day
102.3	111.41	9.11	1345.28	27.45	12/17/21	10/29/21	12/17/21	49	2.27	2.09
88.8	53.63	-35.17	640.43	23.72	1/13/22	12/17/21	1/13/22	27	1.99	3.29
148.7	145.93	-2.77	1702.91	48.65	2/17/22	1/13/22	2/17/22	35	4.17	4.25
34	26.71	-7.29	289.22	41.32	2/24/22	2/17/22	2/24/22	7	3.82	4.86
85.1	81.4	-3.7	956.85	34.17	3/24/22	2/24/22	3/24/22	28	2.91	3.04
36.2	40.66	4.46	477.37	23.87	4/13/22	3/24/22	4/13/22	20	2.03	1.81

Figure 6 shows the propane use trend that the baseline model expected. If the PCM tiles were consistently reducing propane use, all the periods in the study should fall below the trend line. As indicated in the table, two periods showed reduced propane use, but the other periods showed more propane use than the baseline.

Figure 3: Actual propane use during the 2021-2022 heating season compared to the predicted baseline.



Although the research team expected the data to show a decrease in propane use after the PCM tiles' installation, a few factors likely affected the flat results. First, the occupants preferred the temperature setpoint at 72° F, but the PCM tile is rated to change phases at 64° F (Image 3) which could mean that the temperature range over which the heating efficiency is affected by the PCM may be smaller than the temperature range this space experienced. Since the occupants did not program in a schedule setback on the thermostats, the temperature remained at 72° F throughout the heating season. This likely meant that the indoor temperature never dropped low enough for the PCM to crystalize and release its heat. Second, the two periods that showed lower propane use than the baseline were at the beginning and end of the heating season. Since outdoor temperatures were higher than in the middle of the season, the occupants may have reduced the heating setpoint as they became more comfortable with the outdoor temperature. Discussions with the occupants indicated that they typically alter the thermostat based on their comfort on a given day. The reduced heating demand could result in lower indoor temperatures that were closer to the PCM tile rating thus resulting in PCM contribution to heat energy in the space. Finally, this space is small - 500 square feet on the first floor and 500 square feet on the second floor. Further analysis should evaluate whether the energy needed to condition larger spaces would be more amenable to PCM impacts.

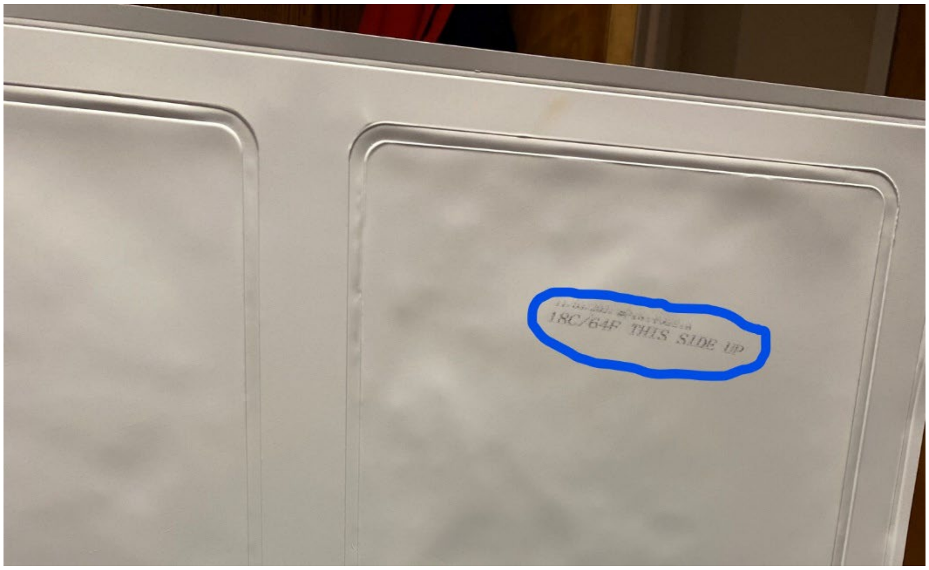


Image 3: PCM tile imprint, showing the crystallization point of 64° F.

The data in this study indicate that specifiers should carefully evaluate the setpoint in a space to ensure they specify the proper PCM rating to ensure there is an energy impact. These data should be assessed in conjunction with additional studies because the space size (1,000 square feet) and number of datapoints are too small to draw conclusions on their own.

PHASE CHANGE TANK

The Woodstock, Vermont, Fire-EMS building contains a tank with organic, plant-based PCM weighing 7.1 pounds per gallon. The PCM tank is integrated into the air-to-water heat pump system via pipe coils running within the material. Efficiency Vermont metered the system to collect its operating data to determine the energy use characteristics. Image 4 shows what the PCM looks like, upon delivery to the tank. The PCM is a granular wax and has the feel and consistency of shredded crayons. Upon solidifying after the first melt, the material will appear as a solid block.

Image 4. PCM is a granular wax and has the feel and consistency of shredded crayons. Upon solidifying after the first melt, the material appears as a solid block.

The tank is located on a second-floor mezzanine and was accessible only by a staircase during the installation process. Thus, the contractor had to carry the granular PCM up to the tank in 5-gallon buckets, until all 4,450 pounds of material was added to the tank (Image 5).

Two of the subsequent best practices deriving from this project were (1) to consider siting the tank on the ground floor because the second-floor of the structure must be designed to support the tank's weight when fully loaded potentially limiting the amount of PCM that can be installed; and (2) to ensure that PCM is installed, when above ground floor level, at a stage of construction when an elevator is available.

Image 4: Tank holding PCM after installation at Woodstock Fire-EMS building.

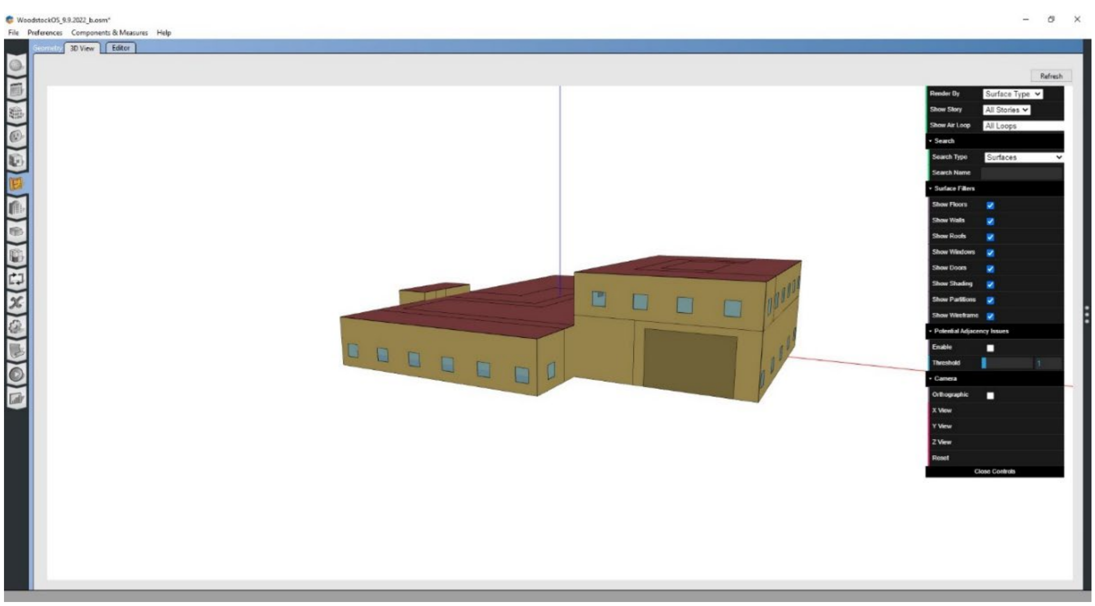
During commissioning, the commissioning agent identified a discrepancy between the specified PCM melt point and the melt point of the product installed. The system is designed for a PCM melt point of 108° F. The research team tested a sample of the PCM in a double boiler and found that it melted at 140° F. Before the system can come online, the PCM must be changed to the correct specification. For this project, the manufacturer and contractors are continuing to supply and install 108° F PCM. Once fully commissioned, the system will begin to operate, and data collection will begin to assess the impact of PCM on the air-to-water heat pump performance.

NEXT STEPS

Mann and Machine installed an air-source heat pump after the heating season was over. The research team installed eGauge meters on the two heat pumps and placed temperature loggers in both heating zones and outdoors. The research team also programmed a night and weekend setback schedule into the heat pumps' controls. The owner prefers the temperature during occupied hours to be at 72° F, so the research team set up the schedule for nights and weekends to drop to 65° F, while maintaining the higher comfort levels on weekdays. The site owner was not comfortable dropping the temperature further, and the heat pump will be able to raise the temperature in the mornings without problems achieving the daytime setpoint before occupancy. The research team will use the meter data after the heating season to build a whole-building energy model with OpenStudio®, which will estimate whether the PCM has any impact on the heat pump efficiency.

The Woodstock Fire-EMS building will complete the PCM swap-out before completing system commissioning. Once the system is operational, the research team will collect data throughout the heating season to assess system performance. The research team will model the building in OpenStudio (Figure 7) and will use the meter data throughout its development. The research team will then adjust the model to show system energy use if it did not have PCM, and the outputs used to determine the energy reduction associated with the PCM.

Figure 4: OpenStudio model of the Woodstock EMS building.



Residential Space Temperature

Energy resilience in residential spaces is becoming a more prevalent topic because severe weather events are increasingly causing prolonged power outages and more customers are reliant on electricity for space and water heating and transportation. Typically, a backup generator will maintain critical loads (those that protect life and property), although backup batteries are becoming more common. Those measures can achieve resilience goals for homeowners; however, not everyone can afford them. With the electrification of thermal and transportation loads, residential scale generators and batteries may not meet the critical load during prolonged power outages.

In this study, Efficiency Vermont evaluated the relationship between winter temperatures in Vermont and the length of time occupants can stay comfortable in their homes during a power outage. The research team estimates the amount of weatherization necessary for a home to increase its temperature "float time"—the length of time occupants of a dwelling can remain comfortable without power—to the desired level.

A research team from the Lawrence Berkeley Laboratory and the U.S. Department of Energy Building Technologies Office evaluated a Florida nursing home's space temperature impacts, using modeling from Hurricane Irma. They found that air sealing and insulation are effective measures for retaining space heating during an outage. Although detrimental in a cooling-dominant climate, such measures are critical in a heating-dominant climate.

STUDY METHODS

Efficiency Vermont recruited five study participants from across the state; three had houses with radiant slabs, and two did not. Each participant installed at least one Ecobee smart thermostat (Image 6) in their home, and the research team placed temperature loggers outside the houses, and inside within a heating zone not served by the Ecobee if there was more than one heating zone. Study participants shared their Ecobee data so that the research team could download and aggregate the temperature data. Participants agreed to simulate a power outage once per month during dates determined by the research team. For the simulated power outages, participants preheated their space by setting all home thermostats between two and four hours in advance of the scheduled "outage" to four degrees above the typical setpoints. During the simulated outage period, the participants turned their thermostats down to four degrees below their typical setpoint, to allow the space temperature to float downward for 6 hours. The research team chose setback days when the forecast was for outdoor temperatures above 20° F, also choosing two to four consecutive days to allow participants to adjust the thermostats on a day that worked for their personal schedules. Solar radiation and internal heat gains were not considered in the data.

Image 5: Ecobee smart thermostat installed in a study participant's home.

Beginning in November 2021 and continuing monthly through April 2022, participants adjusted their space temperatures to simulate the power outages, and the research team downloaded the temperature readings from the Ecobees. The research team collected the temperature loggers in May 2022. Home data, including infiltration test results, were used to create, and calibrate home models in OpenStudio.

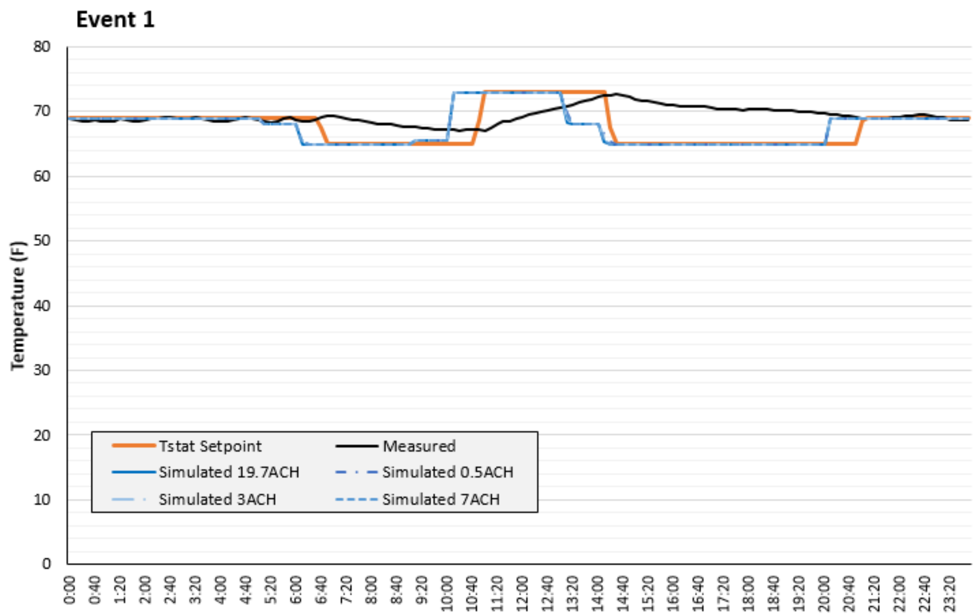
The OpenStudio models were created using the HPXML workflow developed by NREL and commonly used in residential modeling tools like REM/Rate. This method ensures residential models that are consistent with other tools regarding assumptions around various assemblies and appliance energy use.

RESULTS

The initial modeling process exposed shortcomings in the resulting OpenStudio models with respect to the models' ability to replicate thermal decay patterns that aligned with the homes' performance. The initial modeling runs showed that the HPXML-generated OpenStudio models had extremely fast responses to setpoint changes with temperatures often dropping 10° F over the course of thirty minutes. By comparison even homes that are considered "leaky" still had temperature decay time more on the order of 5° F over five hours.

Figure 8 is representative of the initial modeling. The orange line represents the thermostat setting in both the metered house and replicated in the energy model. The blue lines represent the resulting zonal temperature of the house in the energy models. There is a slight time shift that is addressed in later modeling runs. The model shows precipitous drops and rises in temperature in the simulated temperature trend in response to thermostat changes. The model's predictions for house temperature at the zone contrasts with the black line trending the actual temperature from the temperature logger. As a result, the model would not produce accurate temperature decay trends because it estimates that there is a significant temperature drop before a slower temperature float.

Figure 5: OpenStudio result for a home space temperature model showing predicted performance compared to actual performance



The temperature modeling issue is a function of the OpenStudio software which must be addressed by working through the software features with NREL to achieve an accurate model that predicts temperature float time reflective of real-world conditions. Once corrected, the models will provide valuable data for estimating space temperature resilience in Vermont homes to inform outage response, justifying weatherization investment for poor performing homes, and providing occupants with information to inform their decisions about power outages of varying durations. Therefore, the modeling team will continue to work with NREL in the coming year to achieve an effective OpenStudio model that can provide insight to further residential energy resilience planning in the state.

NEXT STEPS

The OpenStudio modeling process provides an opportunity for Efficiency Vermont to work with the OpenStudio team at NREL to improve the functionality and capability for the software to accurately model building systems. Efficiency Vermont will continue to work with the NREL team to introduce thermal storage modeling capabilities and accurate thermal storage representation across various materials. The data collected for this study provides a valuable resource to test further updates in OpenStudio to calibrate the models and ensure accuracy.

In the process of improving OpenStudio software, Efficiency Vermont's modeling and research teams will continue to gather a dataset to show how homes perform relative to indoor temperature, outdoor temperature, building air leakage, and power outage time. Winter Storm Elliot in December 2022 resulted in power outages lasting up to seven days for families who were at home for the holidays. The data the OpenStudio model can provide through the improvement process will help Vermont residents prepare to ride through similar outages in the future with less disruption to their lives.

The research team will also further investigate homes built on slabs containing radiant heat to determine the effect on interior temperature resilience when occupants raise the temperature setpoint to preheat the slab in anticipation of a power outage or demand response event. The expanded scope will evaluate how concrete can serve as a thermal battery in homes.